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On Enhancing Network Reliability and Throughput for Critical-Range Based Applications in UWSNs

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Abstract

Underwater Wireless Sensor Networks (UWSNs) support various applications like pollution monitoring, tsunami warnings, offshore exploration, tactical surveillance, etc. Distinctive features of UWSNs like low available bandwidth, large propagation delay, highly dynamic network topology, and high error probability pose many challenges for designing efficient and reliable communication protocols. In this paper, we propose an extension of IAMCTD (Improved Adaptive Mobility of Courier nodes in Threshold-optimized DBR protocol for UWSNs) that focuses on enhancing network reliability and throughput for critical-range based applications. Our scheme avoids control overhead that was present in IAMCTD for implementing changes in depth threshold. The movement pattern of courier nodes along with reducing communication burden on nodes increases throughput as well. Additionally, stability period is improved and node density per round remains comparatively high improving the overall network reliability. Based on the comprehensive simulations using MATLAB, we observe that our scheme improves the performance in terms of throughput and stability period. Moreover, comparatively higher network density per round is maintained and end-to-end delay is stabilized throughout the network lifetime.

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Keywords: UWSN; courier nodes; depth threshold

1. Introduction

UWSN is an emerging and promising networking realm that serves various applications from scientific and commercial domain to military perspectives [1,2]. Underwater communication is different from terrestrial communication. The protocols proposed for terrestrial sensor networks are not appropraite for UWSNs as they are developed by considering radio signals characteristics like low propagation delay and high bandwidth. The harsh underwater environment and the use of acoustic signals impose many challenges in designing efficient communication and networking protocols for UWSNs. Acoustic signals are used in underwater environment because radio signals get absorbed in water.

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Acoustic signals are having a speed which is five orders of magnitude lesser than radio signals (i.e. 1500 m/s) which produces long propagation latency and end-to-end delay. The available bandwidth is also severely limited (i.e. < 100 kHz). Furthermore, underwater sensor nodes are energy-constrained and their battery replacement is very expensive because of the harsh underwater environment[3,4].

Because of the above mentioned constraints, enhancing network's reliability and throughput in UWSNs serves as a challenge. The routing protocols of UWSNs can be classified into localization based and localization-free routing protocols. However, the localization-free routing protocols are commonly used, because, localization causes much overhead in terms of numerous control messages. Many protocols in MAC, network and transport domain have been proposed for UWSNs taking into account their unique characteristics.

In this paper, we therefore present a routing scheme on enhancing network reliability and throughput for critical-range based applications in UWSNs. In our work, the adaptive changes in depth threshold are independent of the network density information. This avoids the exchange of control packets that was taking place throughout the network life time in IAMCTD[5]. The optimized movement pattern of courier nodes increases throughput while minimizing the burden on medium-depth nodes and reducing the energy consumption of low-depth nodes by utilizing an on-spot data collection mechanism. The stability period is improved and node density remains comparatively high indicating that the network is becoming sparse in a gradual manner which improves the network reliability.

The rest of this paper is organized as follows. In section II, we briey review some related work. In section III, motivation behind this piece of work and our contribution is discussed concisely. Then, in section IV, we present our work in detail.Finally, we present simulation results in section V, followed by our conclusion in section VI.

2. Related Work

In this section, we present some related routing protocols available in the literature. In[1], a novel routing protocol called Depth-Based Routing (DBR) is proposed that uses the depth of the sensor nodes as a routing metric and forwards data towards sink using the greedy approach. In[2], an energy efficient routing protocol, named Energy-Efficient Depth-Based Routing (EEDBR) is presented. EEDBR utilizes depth as well as residual energy of sensor nodes in order to improve the network lifetime. Reliable Energy-efficient Routing Protocol based on Physical distance and Residual energy ($R - ERP^2R$)[3] utilizes physical distance as a routing metric to balance energy consumption among the sensors. Link quality towards the forwarding node and residual energy of the the forwarding node are considered to provide reliability and improved network lifetime. A scheme for time critical applications in UWSNs is proposed in Multipath Power-control Transmission (MPT)[4]. It is a cross layer approach that combines power control with multipath routing and packet combining at the destination. In IAMCTD[5], forwarding function based routing scheme is proposed. It is a novel network prototype in localization-free and flooding based routing for underwater applications.It achieves energy conservation of sensor nodes in UWSNs. Hop-by-Hop Dynamic Addressing Based routing protocol (H2-DAB)[6] achieves minimum delay and higher network lifetime by using hop count as a routing metric. Forwarding is performed on the basis of an address(HopID)that is assigned to each sensor node. It also employs courier nodes to provide adaptability for time-critical and data-sensitive applications.

3. Motivation and contribution

IAMCTD adapts the depth threshold with varying network density. Hence, it requires the exchange of control information at regular intervals. This information exchange while acting as an overhead utilizes network resources. Although the stability period is much improved in IAMCTD, however, the trend of instability period is not balanced. It indicates a non-uniform reduction in network density per round. Moreover, the movement pattern of courier nodes is not optimized to reduce burden on medium depth nodes which greatly reduces throughput and overall network performance. In our work,

- The changes in depth threshold are independent of the network density information, avoiding the exchange of control packets throughout the network life time.

- The optimized movement pattern of courier nodes minimizes the burden on medium depth nodes. It also decreases the energy consumption of low-depth nodes utilizing on-spot data collection, collectively increasing throughput.
- Stability period is improved and the node density remains comparatively high indicating that the network is becoming sparse in a gradual manner, improving the network reliability.

Hence, we promote global load balancing in our proposed scheme by modifying the IAMCTD protocol for critical-range based applications. Based on the above analysis, this paper presents a scheme on enhancing network reliability and throughput for critical-range based applications to accomplish resourceful energy expenditure of nodes in UWSNs.

4. Proposed scheme

In this section we present our work. The following sub-sections give a detailed view about our scheme.

4.1. Network Architecture

Numerous sensor nodes are randomly deployed in the area to be monitored. Sink nodes are deployed on the water surface and courier nodes are deployed in water at different depths. Courier nodes follow a horizontal pattern of movement. The sensor nodes use acoustic modems whereas the sink nodes and courier nodes are equipped with both acoustic and radio modems. As radio communication is 5 times faster than acoustic communication, a data packet once received at any sink or courier node is considered delivered to the on-shore data center. As depth of the courier nodes remains fixed, they relay data to the sink by forwarding it to other courier nodes having lesser depth. Nodes share their depth and residual energy information with each other in the knowledge acquisition phase.

4.2. Underwater Channel Model

The channel model used to calculate signal attenuation and total noise loss in underwater acoustics is detailed here. We are interested in working out total attenuation of signal on the basis of spreading loss[8] and signal absorption loss. Thorps channel model calculates absorption loss $\alpha(f)$[?] at a given frequency f as follows:

$$10log\alpha(f) = \begin{cases} 0.11f^2/(1+f^2) + 44f^2/(4100+f) & \\ +2.75 * 104f^2 + 0.003 & f \leq 0.4 \\ & \\ 0.002 + 0.11(f/(1+f)) + 0.011f & f < 0.4 \end{cases} \tag{1}$$

Here $\alpha(f)$ is in dB/km and f in kHz. We determine the value of α by using the value of absorption loss, as follows:

$$\alpha = 10^{\alpha(f)}/10 \tag{2}$$

likewise, all tunable parameters are given in dBreμPa. The total attenuation $A(l, f)$ can be computed by combining absorption loss and spreading loss, as follows:

$$10log(A(l, f)) = k * 10log(l) + l * 10log(\alpha(f)) \tag{3}$$

Where, first term corresponds to spreading loss and the second term to the absorption loss. The spreading coefficient k defines the geometry of the signal propagation in underwater acoustics (i.e., $k = 1$ for cylindrical, $k = 2$ for spherical, and $k = 1.5$ for practical spreading[9]).

The ambient noise in underwater networks is composed of turbulence noise, shipping noise, wind noise and thermal noise. The power spectral density[8] of the four noise components in dBreμPa is given by the following formulae as a function of frequency in kHz :

$$10log(N_t(f)) = 17 - 30log(f), \tag{4}$$

$$10log(N_s(f)) = 40 + 20(s - 0.5) + 26log(f) - 60log(f + 0.03), \tag{5}$$

$$10log(N_w(f)) = 50 + 7.5w^{1/2} + 20log(f) - 40log(f + 0.4), \tag{6}$$

$$10log(N_{th}(f)) = -15 + 20log(f), \tag{7}$$

where N_t, N_s , N_w and N_{th} represent turbulence noise, shipping noise, wind noise and thermal noise. The overall noise power spectral density [7] can be calculated as:

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f) \tag{8}$$

4.3. Network Initialization Phase

Because of the knowledge acquisition phase, all nodes are aware of each others' depth. In the network initialization phase nodes find their neighbors. Neighbors selection is based on transmission range and depth information. A node is selected as neighbor if it is laying at similar or lesser depth. Depth threshold is selected on the basis of number of neighbors. Depth threshold is used to avoid flooding. Nodes forward their data by utilizing this depth threshold value. In this way, global knowledge of network density is not required and nodes adapt their depth threshold based on their alive neighbors. During this phase, each node is advised to keep on identifying its alive neighbors at regular intervals to adapt the depth threshold accordingly.

4.4. Critical-range Based Data Sensing

Traditional routing schemes consume surplus energy because of transmission of redundant data and retransmission of critical data. We exploited critical-range based data sensing and routing. This critical-range is specified on an application basis. Algorithm 1 depicts the involved procedure. After network initialization, nodes start sensing the specified environmental attribute. If the sensed value is greater than or equal to H_{th}, flag field of the data packet is set to 1. Then, this data packet is forwarded if node's residual energy R_i is sufficient for transmission. The other scenario is that if the sensed value is lesser than H_{th} but greater than or equal to S_{th}. In this scenario, node sets flag field of the data packet to 0 and performs forwarding if it is having enough residual energy R_i. Here, flag field is appended to the basic packet structure in order to indicate severity of the sensed attribute, so that appropriate measures can be adopted at the on-shore data center.

The proposed scheme is applicable for many scientific applications that observe the environment; from geological processes on the ocean floor, to water characteristics (temperature, salinity, oxygen level, bacterial and other pollutant content, dissolved matter, etc.) to counting or imaging animal life (microorganisms, fish or mammals) [11].

Algorithm 1 Data Sensing and Routing

```
S ← Sensed attribute
H_th ← Hard threshold
S_th ← Soft threshold
P ← Data packet
R_e ← Residual energy
F ← Flag
if S ≥ H_th AND R_i > 0 then
    send P
    set F = 1
else if S_th ≤ S < H_th AND R_e > 0 then
    send P
    set F = 0
else
    no transmission
end if
```

4.5. Data Routing Phase

Data generated as a result of the sensing process is to be routed to the sink. For this purpose, a source node forwards data packets to in-range courier node. On reception of data, courier node commands the source node to avoid further flooding of this data. In the absence of courier node, source node forwards data to neighbors based on its depth threshold. Receiving (relaying) nodes keep the received packets in buffer and perform forwarding on the basis of holding time. Holding time is calculated by using the forwarding function. Forwarding function is depth dependent and is different for nodes with different depths. Along with this, priority queue is maintained at relaying nodes in order to avoid transmission of same data packets. This mechanism reduces end-to-end delay of critical data.

Data packet is composed of header and payload. Header contains the control information which is necessary for data routing whereas payload is the actual data to be transmitted. Format of data packet that is used in our scheme is shown in fig. 2

Flag	Sender ID	Packet Sequence No.	Depth	Payload

Fig. 1: Format of data packet

4.5.1. Depth Threshold Selection Process

Algorithm 2 Depth Threshold Selection

$R \leftarrow$ Current round
$R_{max} \leftarrow$ Maximum number of rounds
$N \leftarrow$ Number of a node's neighbors
$D_{th} \leftarrow$ Depth threshold
$D_{th1}, D_{th2}, D_{th3} \leftarrow$ Optimal values of depth threshold
for $R = 1 : 1000 : Rmax$ **do**
  if $N \geq 9$ **then**
    $D_{th} = D_{th1}$
  else if $9 < N \geq 5$ **then**
    $D_{th} = D_{th2}$
  else if $N < 5$ **then**
    $D_{th} = D_{th3}$
  end if
end for

During the network initialization phase, each node is advised to keep on identifying its alive neighbors at regular intervals to adapt the depth threshold accordingly. Depth threshold selection process of nodes is shown in fig. 3. The three optimal values of depth threshold (D_{th1}, D_{th2} and D_{th3}) are adapted on the basis of number of alive neighbors of a node. The whole procedure is shown in algorithm 2.

4.5.2. Mobility Pattern of Courier Nodes

Introduction of courier nodes in UWSNs is an ingenious way of improving network stability and reliability. Deployment of courier nodes in a network avoids distant transmissions and greatly reduces load from medium-depth nodes by acting as a relay. Sojourn tour specified by the sink defines the mobility pattern of a courier node. In our scheme, courier nodes follow a horizontal movement pattern that remains fixed throughout the network lifetime. After network initialization, courier nodes begin their movement and collect data from nodes in their vicinity. Mechanical modules are used by courier nodes to maintain their depth and movement pattern[6].

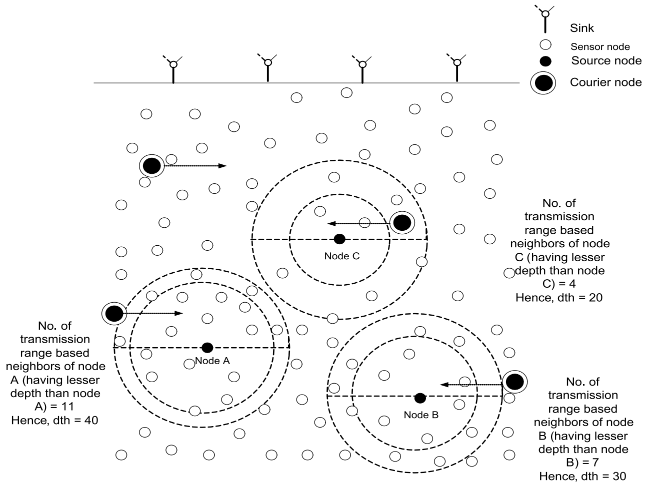


Fig. 2: Depth threshold selection (D_{th1} = 40, D_{th2} = 30, D_{th3} = 20)

4.5.3. Holding Time Computation on the Basis of Forwarding Function

Holding time is the time for which node holds the data packets in its buffer before forwarding. It is given by the following formula:

$$H_T = (1 - F_F)H_{tmax}, \tag{9}$$

where H_T represents the holding time and F_F represents the value of forwarding function. H_{tmax} denotes the maximum holding time which is selected according to the environmental conditions.

A node selects its F_F on the basis of its depth, residual energy and SNR. There are three main F_F: Signal Quality Index (SQI), Energy Cost Function (ECF) and Depth Dependent Function (DDF)[5]. Among the set of neighbors, a node having highest F_F acts as an optimal forwarder because it has minimum holding time.

Upper region of water suffers from maximum interference, noise and shipping activities. Hence, to reduce the effect of these losses on signal strength, SQI is used as a forwarding function. It is represented as

$$SQI = (LSNR(R_i))/l_i, \tag{10}$$

where LSNR is the localization free signal to noise ratio, l_i is the depth difference between sender and receiver node.

There is a huge burden of data forwarding on nodes lying in medium depth region. Hence, to utilize their energy efficiently while taking into account their residual energy, ECF is used as the forwarding function to attain global load balancing. ECF is represented as

$$ECF = priority_{value}(R_i)/D_i, \tag{11}$$

where $priority_{value}$ is a constant that can be adjusted according to stability requirements, D_i is the depth of the i_{th} receiver node.

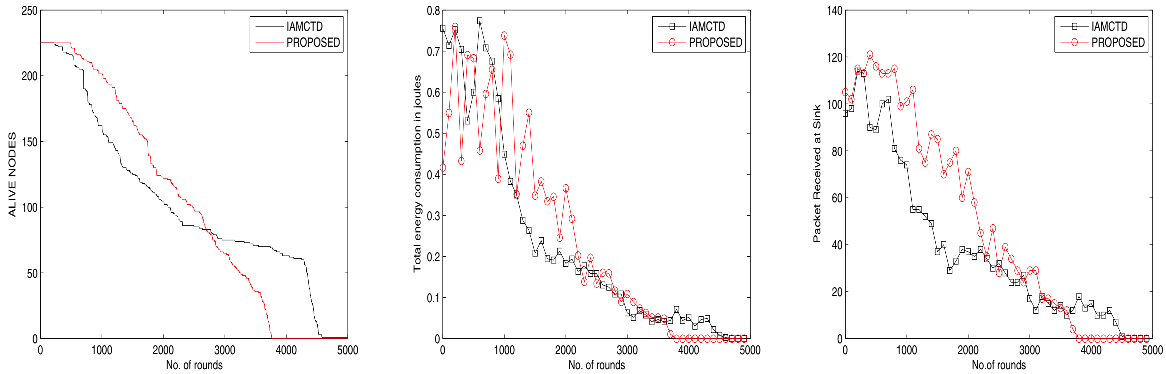
Nodes laying in high depth region have to perform distant transmissions. Side by side, flooding is more prominent in this region. Hence, to reduce these phenomena, DDF acts as the forwarding function which takes into account both signal strength and residual energy while selecting the optimal forwarder. Following is the expression for DDF

$$DDF = LSNR(R_i)/D_i, \tag{12}$$

5. Results and discussion

We perform simulations of our proposed scheme in MATLAB and compare it with IAMCTD. Sensor nodes are 225 in number and they are randomly deployed in underwater environment in an area of 500 m x 500 m. Four sinks are located on the water surface and they are 100 m apart from each other. Four courier nodes are deployed in water at different depths and they are following a horizontal movement pattern. Each node is equipped with an initial energy of 5 J and is having a fixed transmission range of 100 m. Size of data packet is 50 byte. The acoustic modem used is LinkQuest UWM1000 [12] which has a bit rate of 10 kbps. Power consumption of a node in transmitting, receiving and idle modes is 2W, 0.1W and 10mW respectively. Following evaluation metrics are considered:

- *Alive nodes:* It shows the number of nodes which have a residual energy sufficient for data transmission.
- *Average energy consumption:* It is the average energy consumed by all alive nodes per round.
- *Throughput:* It is the total number of packets received at sink per round.
- *End-to-end delay:* It represents the average time taken by a packet to travel from source to sink.
- *Transmission loss:* It shows the average transmission loss (dBs) between source node and sink in one round.



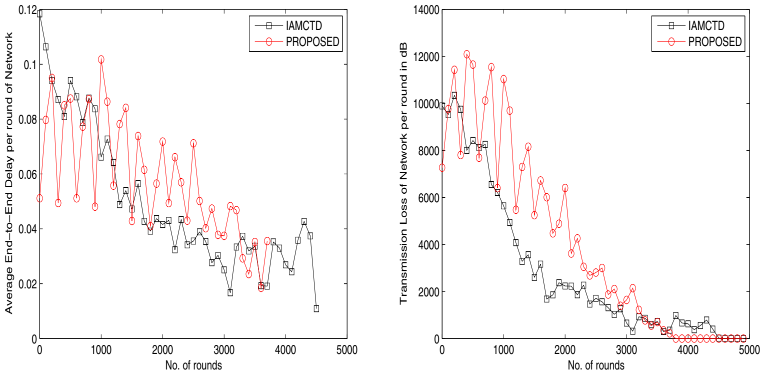
(a) Comparison of alive nodes in the network (b) Comparison of average energy consumption of nodes in the network (c) Comparison of packets delivered to sink

Fig. 3: Simulation results for proposed scheme

As shown in fig. 4(a), the stability period and number of alive nodes per round are improved in our scheme. The node density per round is comparatively high till 2800 rounds indicating that the network is becoming sparse in a gradual manner, improving the overall network reliability. However, the network lifetime is reduced as compared to IAMCTD at the cost of high throughput. High throughput indicates more number of transmissions and increased energy consumption per round which in turn reduces the network lifetime. Fig. 4(b) shows the comparison of average energy consumption of nodes in the network. Energy consumption is high in our scheme because of more number of transmissions. As shown in fig. 4(c), throughput is increased in our scheme because of selection of optimal data forwarders (by varying the depth threshold according to a nodes alive neighbors) and favourable mobility pattern of courier nodes. End-to-end delay is shown in fig. 5(a), it follows almost the same trend throughout the network lifetime in our scheme. End-to-end delay is less for up to 1000 rounds as compared to IAMCTD and follows almost the same pattern afterwards. In IAMCTD throughput decreases drastically after about 800 rounds because of which the end-to-end delay is reduced, whereas in our scheme it remains stable because of maintaining a high throughput. Transmission loss is distance dependent. Fig. 5(b) shows that high throughput is achieved at the cost of increased transmission loss.

6. Conclusion

In this article we proposed a scheme for enhancing network reliability and throughput for critical range based applications in UWSNs. The proposed scheme is devised, taking into account multiple metrics, that is, depth, residual energy and SNR. It operates in different phases, namely knowledge acquisition phase, network initialization phase



(a) Comparison of end-to-end delay

(b) Comparison of transmission loss in the network

Fig. 4: Simulation results for proposed scheme

and critical-range based data sensing and routing phase. During the knowledge acquisition phase, nodes share their depth and residual energy information. During the network initialization phase, each node is advised to calculate the number of its alive neighbors at regular intervals to adapt the depth threshold accordingly. In the critical-range based data sensing and routing phase, nodes sense data on the basis of the defined critical-range and forward it to in-range courier nodes or depth threshold based neighbors. We implemented our proposed work in MATLAB and evaluated its performance by comparing it with IAMCTD with respect to stability period, network density, throughput, energy consumption, end-to-end delay and transmission loss. Based on the comprehensive simulation, we observed that our work contributes to the performance improvements in terms of improved stability period, comparatively higher network density, high throughput and stabilized end-to-end delay. However, high throughput is achieved at the cost of increased transmission loss.

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